# AquaData and AquaGIS: Two computer utilities for temporal and spatial simulations of water-limited yield with AquaCrop

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A B S T R A C T

The crop simulation model AquaCrop, recently developed by FAO can be used for a wide range of purposes. However, in its present form, its use over large areas or for applications that require a large number of simulations runs (e.g., long-term analysis), is not practical without developing software to facilitate such applications. Two tools for managing the inputs and outputs of AquaCrop, named AquaData and AquaGIS, have been developed for this purpose and are presented here. Both software utilities have been programmed in Delphi v. 5 and in addition, AquaGIS requires the Geographic Information System (GIS) programming tool MapObjects. These utilities allow the efficient management of input and output files, along with a GIS module to develop spatial analysis and effect spatial visualization of the results, facilitating knowledge dissemination. A sample of application of the utilities is given here, as an AquaCrop simulation analysis of impact of climate change on wheat yield in Southern Spain, which requires extensive input data preparation and output processing. The use of AquaCrop without the two utilities would have required approximately 1000 h of work, while the utilization of AquaData and AquaGIS reduced that time by more than 99%. Furthermore, the use of GIS, made it possible to perform a spatial analysis of the results, thus providing a new option to extend the use of the AquaCrop model to scales requiring spatial and temporal analyses.

*Keywords:*
Software tool
AquaCrop
Crop simulation model
Geographic information system
Spatial aggregation

## 1. Introduction

The use of crop simulation models in crop production, irrigation management, cropping systems analyses and climate change impacts has proven to be valuable in improving our knowledge of the functioning of agricultural systems (Fraisse et al., 2006; Thorp et al., 2008; Casadesús et al., 2012). Crop models simulate crop growth under different environmental and management conditions, taking into account various limiting factors, thus they are also good tools to assess the temporal and spatial variability of crop behavior over large area scales (Safir et al., 2008; Bergez et al., 2012; Salmon-Monviola et al., 2012; Resop et al., 2012), and they may reduce the needs for lengthy and expensive field experimentation. The extension of crop simulation beyond the individual field scale meets the requirements of an emerging need supporting decision-making in agriculture at several scales, through either spatial or long-term analyses for policy formulation.

In this context, the Food and Agriculture Organization (FAO) has developed AquaCrop (Steduto et al., 2012), a crop water productivity model focused on simulating water-limited attainable yield. The information provided by AquaCrop may be applied in a myriad of ways and by many different types of users, depending on the objective and on the spatial and temporal scale of the analysis (Fereres et al., 2012). The simulation outputs may also be inputs of other types of tools and models. AquaCrop has been broadly tested for different crops around the world under diverse environments (e.g., Hsiao et al., 2009 for maize; García-Vila and Fereres, 2012 for cotton; Abrha et al., 2012 for barley). It has also been used to design different deficit irrigation strategies (Geerts et al., 2010), to evaluate sowing strategies in a semi-arid environment (Abrha et al., 2012), and to develop an economic model for decision support system at the farm scale (García-Vila and Fereres, 2012). Most of the studies so far have been focused on applications at the operational and tactical level, running AquaCrop at the field scale, facilitated by its user-friendly interface (Raes et al., 2009), albeit designed for single runs. For applications at the strategic level, AquaCrop should be applied over large areas or for long time periods, requiring a much larger number of model runs, a feature that is not possible with the standard AquaCrop version. The development of a new AquaCrop plug-in program by FAO (FAO, 2012) has facilitated the option of multiple simulations, by running a pre-defined list of projects in the standard user interface of the AquaCrop program (FAO, 2012). However, there is still the need to manually create the input files and the project files thus, requiring lengthy times to scale up AquaCrop applications from a few simulations to multiple runs. For these reasons, the development of a tool that generates the input and project files of the plug-in version of AquaCrop while at the same time allowing easy visualization of the results would be highly desirable for many model applications. Earlier publications providing software applications to complement simulation models in input/output processing and calibration include Thornton et al. (1995), Ascough et al. (1998) and Thorp et al. (2008), with very satisfactory results. To address the temporal and spatial variability of diverse parameters over the territory, the interpretation of simulation outputs can be significantly enhanced by linking the crop model results with software that facilitates spatial analysis and visualization through mapping (Yang et al., 2011). In the coming years, the integration of GIS and Internet (Mendicino and Versace, 2007) will be an essential tool for improving the diffusion of technology and improved practices among farmers and technicians (Lorite et al., 2012).

This work was undertaken to eliminate the tedious task of manually generating the AquaCrop input and project files needed to feed massive runs, and to adapt it to a GIS platform. We describe here two new tools, AquaData and AquaGIS, developed to manage the AquaCrop inputs and outputs, including a GIS for spatial analysis of the results. AquaData and AquaGIS are independent tools and could be executed separately. However, in order to facilitate the applicability of the tool, AquaData was imbedded in AquaGIS, generating a single package, from the input files to the visualization of the AquaCrop results. To illustrate the use of the new tools and to demonstrate their advantages, a case study that simulates climate change impacts on wheat yields for the Region of Andalusia, Spain, is presented.

## 2. Materials and methods

### *2.1. AquaCrop description*

The AquaCrop crop model simulates attainable yields for herbaceous crops as a function of water consumption under different irrigation regimes (Steduto et al., 2012). AquaCrop directly links crop yields to water use and, estimates biomass production from actual crop transpiration through a normalized water productivity parameter, which is the core of the AquaCrop growth engine (Steduto et al., 2012). A full description of the conceptual basis and principles of AquaCrop are found in Steduto et al. (2012). The model version used in this work is the version 3.1+ that was launched on March 2011.

#### *2.1.1. Description of input files*

Relative to other crop simulation models, AquaCrop requires a low number of input data to simulate the yield response to water (Steduto et al., 2012). In AquaCrop, the input files can be grouped into projects. Each project contains up to 11 input files (text files with the appropriate extension for each file type) aggregated by topics. Thus, a single run requires up 12 files as listed in Table 1, which includes the project file. Those files marked with an asterisk are not mandatory for a simulation run of AquaCrop. Input files could be easily created or changed using the user-interface of AquaCrop software (Raes et al., 2009). However, when it is necessary to perform many simulations (e.g., applications to large areas or long-term analyses), the generation of the high number of input files becomes tedious and time consuming.

#### *2.1.2. Description of output files*

AquaCrop (standard version) plots simulation results as various graphs which are updated each daily time step, and they can also be displayed as numerical outputs (Steduto et al., 2012). The simulation results are recorded in output files, and can be aggregated into 10-day, monthly or yearly data. The output consists of five files containing data about: crop growth and production, soil water balance, soil water content, soil water content – compartments (including water content at different depths), and net irrigation requirements. All these data can be retrieved in spread sheet programs for further processing and analysis (Steduto et al., 2012).

### *2.2. AquaCrop plug-in program (version 3.1+)*

For a large number of model runs, FAO now provides the AquaCrop plug-in program, performing identical calculation procedures as the AquaCrop standard program (Raes et al., 2012). The plug-in program facilitates the inclusion of AquaCrop in external applications. However, only simulation runs (single or multiple) previously defined can be carried out with the AquaCrop plug-in program due to the absence of a user interface (Raes et al., 2012). The inputs of the program are sorted in text files (Table 1), which could be created until now with the user interface of the AquaCrop model or using any existing text file for input and manually replacing the values of the variables with the new values, while keeping the format and line spacing exactly as they are in the original text file, and then saving it as a new file. The plug-in program runs the successive projects and the intermediate (daily, 10-daily or monthly) and final (seasonal) simulation results of each project are saved in an output file, which contains information on the simulation period, climatic and soil water balance parameters, stresses, biomass production, crop yield and water productivity (Raes et al., 2012). However, AquaCrop plug-in provides individually these text files for each project simulation run, making it difficult to process all the individual data when the number of fields/years/management strategies simulated is high.

### *2.3. AquaData software*

AquaData is a tool programmed in Delphi v. 5 developed here to facilitate the use of AquaCrop for multiple simulation runs, where the manual generation of the required high number of input files (Table 1) is not feasible. This utility helps the user create the appropriate AquaCrop input files, reducing substantially the time required for this task.

#### *2.3.1. Main database and input databases*

AquaData automates the generation of input files needed to run AquaCrop. To carry out this automation the application requires knowledge of the basic data for each execution (denominated project in AquaCrop). These basic data are stored in a database (hereafter called Main Database; MD) that contains, for each project, information indicating the beginning of the simulation and sowing date, the irrigation schedule and initial soil water content at the start of the simulation. In addition, MD also includes the name and location of the climate, soil, irrigation, crop and atmospheric $[CO_2]$ inputs files for each project (Table 1). All the information is stored in one row, for each project. In the current version of AquaData, MD is a dBase file and could be manually generated from a text file of spreadsheet. Table 2 presents an example of the main database required by AquaData. As the construction of MD when the number of AquaCrop projects is high could be tedious, a specific module imbedded in AquaData automatically develops the MD database (Fig. 1). This module requires very limited input data such as the period of study, weather station or soil identification.

In addition to MD, three input databases are required: weather, soil and irrigation data. These three databases are stored in dBase files and do not require any specific order of listing of the data. dBase files are easily generated from text files or spreadsheets. Finally crop parameters and $[CO_2]$ variations with year are obtained

**Table 1**
Filenames, extension, description and main inputs for each input file required for AquaCrop. Those filenames marked with an asterisk are not mandatory for a simulation run.

| Filename | Extension | Description | Main Inputs |
|---|---|---|---|
| Project | .PRO | Defines the specific inputs required by AquaCrop for each run | – Folder for inputs/outputs<br>– Input file names<br>– First/last day of simulation<br>– First/last day of cropping<br>– Crop parameters |
| Climate | .CLI | Defines the different climate input files | – TMP, ET0 and PLU filenames<br>– $CO_2$ filename |
| Temperature | .TMP | Defines temperatures | – Temporal variation<br>– Minimum temperature<br>– Maximum temperature |
| Reference ET | .ET0 | Defines reference evapotranspiration | – Temporal variation<br>– Reference ET |
| Rain | .PLU | Defines rainfall | – Temporal variation<br>– Rainfall |
| Atmospheric $CO_2$ | .$CO_2$ | Defines the default mean annual atmospheric [$CO_2$] from 1902 to 2099. Some default [$CO_2$] files are available (Hsiao et al., 2012) | – $CO_2$ concentration |
| Crop | .CRO | Defines the complete set of required crop parameters (Raes et al., 2009). FAO has calibrated crop parameters for several crops (Steduto et al., 2012) | – Base/upper temperatures<br>– Soil water depletion factors<br>– Root depth<br>– Shape factor for stress<br>– CGC, CCx, CDC coefficients<br>– Length of stages |
| Irrigation* | .IRR | Defines information about the irrigation schedule | – Irrigation method<br>– % Soil surface wet<br>– Date/depth by irrigation event |
| Management* | .MAN | Defines the soil fertility level and soil conservation practices that affect the soil–water balance | – Soil fertility level<br>– Mulching/soil bunds<br>– Reduction of runoff |
| Soil | .SOL | Defines the soil properties. An example is described in Fig. 2 | – Number of the soil horizons<br>– Thickness of the soil horizons<br>– Water content at FC/PWP<br>– Curve Number<br>– Saturated hydraulic conductivity<br>– Depth of restrictive layer |
| Initial conditions | .SW0 | Defines the soil profile layers at the start of the simulation period | – Water content of each layer<br>– Thickness of each layer |
| Off Season* | .OFF | Defines the off-season (outside the growing season period) practices | – % Ground surface covered<br>– Soil evaporation reduction<br>– Irrigation (date and depth) |

directly from the default files provided by the AquaCrop program, although both the crop parameters and [$CO_2$] variation may be modified by the user.

AquaData (thanks to the programming tool used for its development) gains access to the external databases (dBase files) fast and reliably, as described later (see Section 2.3.3).

*2.3.2. File templates*

AquaData execution requires the production of a text template for each of the input files needed in AquaCrop (Table 1 and Fig. 1). Each text template complies exactly with the format requirements of AquaCrop input files, and contains markers for all the variables included in each input file (Table 3). These file templates were created from default input files, replacing each variable by a text marker. Each marker is unique. Some of the markers for weather data, irrigation and soil files, which are, indicated by an asterisk in Table 3, allowed the inclusion of multiple values (one for each irrigation event, daily $ET_o$, temperature or rainfall, or different soil layers).

For each project stored in MD, the application defines the 12 inputs files required by AquaCrop (Table 1). These 12 new files are built using a copy of the file templates previously defined. An example of a template file for soil characterization (.SOL) with markers, and their replacement by current data is shown in Fig. 2a and b respectively. Here some soil/field characteristics such as curve number, soil layer thickness and hydraulic properties are included.

*2.3.3. AquaData procedures*

AquaData starts reading the main database and all input databases. This procedure is fast and accelerates the following computation steps because the access to the information is faster if the data are stored in the memory, rather than being accessed datum after datum each time in the databases. The data read from the input databases are then stored in multidimensional matrices. Correct sorting of these data is essential to obtain fast access to the information.

The main database (MD) is the engine of the iteration process carried out by AquaData. AquaData, guided by MD, generates for each project a copy of the input templates, and replaces each marker located in each template copy file by the appropriate input

**Table 2**
Example of the main database required by AquaData. P1 and P2 are examples of two projects for different fields and years.

| COD | ORDER | P1 | P2 |
|---|---|---|---|
| Plot | 1 | P3832_A2_72 | H1518_CU_80 |
| File name | 2 | P3832_A2_72 | H1518_CU_80 |
| First day of cropping | 3 | 20_11_2071 | 20_11_1979 |
| Atmospheric $CO_2$ | 4 | MaunaLoa | MaunaLoa |
| Crop | 5 | TrigoGDD-GIS | TrigoGDD-GIS |
| Soil | 6 | S1 | S2 |
| Path | 7 | C:/FAO/Aquacrop/ Data/ | C:/FAO/Aquacrop/ Data/ |
| Place | 8 | P3832 | H1518 |
| Daily records | 9 | 1 | 1 |
| First day of record | 10 | 1 | 1 |
| First month of record | 11 | 9 | 9 |
| First year of record | 12 | 2071 | 1979 |
| Number of records | 13 | 487 | 487 |
| Irrigation method | 14 | 0 | 0 |
| Percentage of soil wetted | 15 | 0 | 0 |
| Irrigation schedule | 16 | 0 | 0 |
| Irrigation season | 17 | 2072 | 1980 |
| SW0_1 | 18 | 0 | 0 |
| Depth_1 | 19 | 60 | 60 |
| SW0_2 | 20 | 80 | 80 |
| Depth_2 | 21 | 150 | 150 |
| Weather Station | 22 | P3832_A2 | H1518_CU |
| Depth_3 | 23 | 150 | 150 |

variable value obtained from the input databases. All the markers used for each input file are described in Table 3. The replacement is carried out by AquaData searching for the markers inside the template files. Once the application identifies a marker, this is replaced by the corresponding input value. The replacement is made while keeping the format unaltered to avoid problems with AquaCrop execution. Finally, all the input files generated by each project are placed in the folder indicated in the main database. These files could be used directly by AquaCrop or used by AquaGIS as described below.

Although AquaData has been designed to be used with the AquaCrop model, the input preparation methodology described here could be applied to any crop simulation model whose input files are stored as text files. For this purpose, only minor modifications of the original code of AquaData would be required.

### *2.4. AquaGIS description*

AquaGIS is a new tool built to execute AquaCrop automatically for multiple fields and multiple seasons (i.e., multiple projects) over a landscape or region, and to process the simulated results (outputs) for interpretation and analysis and spatial visualization. AquaGIS was programmed in Delphi v. 5 and in the GIS programming tool MapObjects. The software consists of two different modules (Execution and Visualization modules; Fig. 3) and uses the AquaData software for input file generation (in fact, the AquaData tool has been included in the AquaGIS software to facilitate the use of the visualization tool).

#### *2.4.1. Execution module*

This module leads the interaction process between the two different software packages (AquaCrop plug-in and AquaData) and the input/output files (Fig. 3) guided by the main database of AquaData (Table 2). With this module, the AquaCrop plug-in program is launched, running one by one the projects listed in the main database and using the AquaCrop input files provided by AquaData. After the runs, the output text files (OUT file) described above (see Section 2.2) are obtained for each project.

The OUT file provided by AquaCrop plug-in contains daily (or 10-daily or monthly) results for a single project. Such file has a fixed structure and cannot be modified by the user. To read the OUT files, some markers have been defined to manage the small format variations of the OUT files (e.g., negative values, number of decimals, etc.).

When all the AquaCrop simulations (using the plug-in program) have been completed, the execution module reads the OUT files and arranges the results for all the analyzed projects in databases sorted by categories. A total of 24 databases are generated, one for each variable (see Section 2.2). The structure of these databases distributed the days in rows and one column for each project. In addition, the last line of OUT files, which contain the seasonal

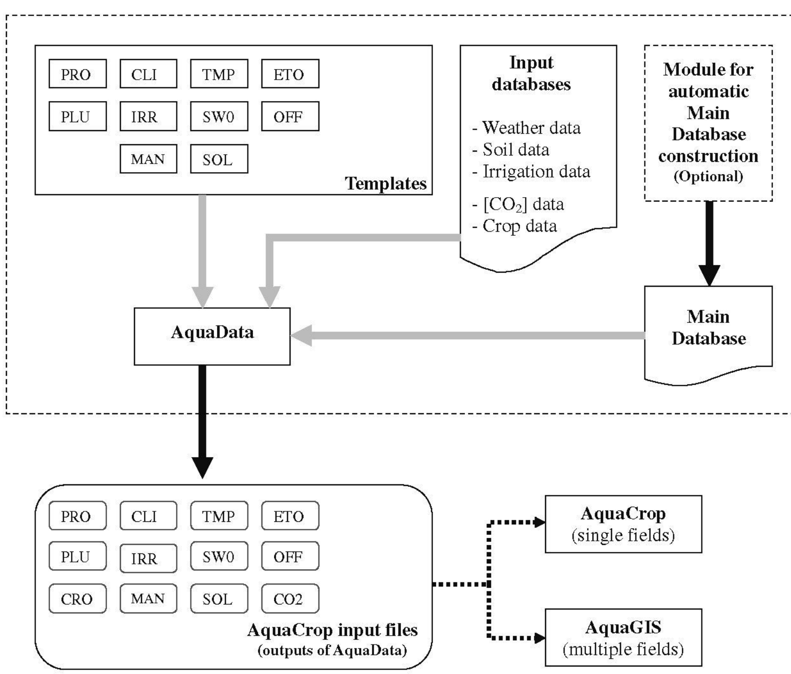



**Fig. 1.** Diagram of AquaData, including inputs (templates, main database and input databases) and outputs (AquaCrop input files). The module for automatic main database construction is optional because the main database could be manually constructed from a text file or spreadsheet without using this module.

**Table 3**
Description of data and markers included in each template input file. Markers with asterisk are repeated for each day, soil layer or irrigation event.

| Input file | Marker | Description |
|---|---|---|
| IRR file | COD_PLOT | Location |
| CLI file | COD_PLACE | Location |
| | COD_FTMP | TMP file |
| | COD_ETO | ETO file |
| | COD_FPLU | PLU file |
| | COD_FCO2 | $CO_2$ file |
| TMP file | COD_PLACE | Location |
| | COD_DR123 | Temporal resolution |
| | COD_FDOR | First day of record |
| | COD_FYOR | First month of record |
| | CTMIN* | Minimum temperature |
| | CTMAX* | Maximum temperature |
| ETO file | COD_PLACE | Location |
| | COD_DR123 | Temporal resolution |
| | COD_FDOR | First day of record |
| | COD_FMOR | First month of record |
| | COD_FYOR | First year of record |
| | CETO* | Reference ET |
| PLU file | COD_PLACE | Location |
| | COD_DR123 | Temporal resolution |
| | COD_FDOR | First day of record |
| | COD_FMOR | First month of record |
| | COD_FYOR | First year of record |
| | CRAIN* | Rainfall |
| SW0 file | COD_WS | Water stored soil bunds |
| | COD_NLY | Number of layers |
| | TH_LY* | Thickness of layers |
| | CSW0_LY* | Soil water content |
| OFF file | COD_PGSMB | % Mulch before season |
| | COD_PGSMA | % Mulch after season |
| | COD_EMRSE | Effect mulch evap reduction |
| | COD_NIB | Irrigation before season |
| | COD_NIA | Irrigation after season |
| | COD_PSWI | % Soil wetted off season |
| | CDAY_B* | Date irrig. before season |
| | DEPTH_B* | Depth irrig. before season |
| | CDAY_A* | Date irrig. after season |
| | DEPTH_A* | Depth irrig. after season |
| PRO file | COD_FDOSP | First day of simulation |
| | COD_LDOSP | Last day of simulation |
| | COD_FDOCP | First day of cropping |
| | COD_LDOCP | Last day of cropping |
| | COD_FCLI | Climate file |
| | COD_FTMP | Temperatures file |
| | COD_FETO | Reference ET file |
| | COD_FPLU | Rainfall file |
| | COD_FCO2 | $CO_2$ file |
| | COD_FCRO | Crop file |
| | COD_FIRR | Irrigation file |
| | COD_FMAN | Management file |
| | COD_FSOL | Soil file |
| | COD_FSWO | Initial conditions file |
| | COD_FOFF | Off season file |
| | COD_PATHN* | Path input files |
| SOL file | COD_PLACE | Location |
| | CCN | Curve number |
| | CREWFTL | Readily evap. top layer |
| | CNSH | Number soil horizons |
| | DRS | Depth restrict. soil layer |
| | CTHICKN* | Thickness of layers |
| | CSATN* | Saturation layer |
| | CFCN* | Field capacity layer |
| | CWPN* | Wilting point layer |
| | CKSATN* | K saturation layer |
| MAN file | COD_PGSM | % Covered by mulch |
| | COD_EMSE | Effect mulch soil evap. |
| | COD_NLSF | % Soil fertility stress |
| | COD_HSB | Height of soil bunds |
| | COD_SRFS | Runoff prevented |
| IRR file | COD_PLOT | Location |

**Table 3** (*continued*)

| Input file | Marker | Description |
|---|---|---|
| IRR file | COD_PLOT | Location |
| | COD_IM | Irrigation method |
| | COD_POSWBI | % Soil wetted irrigation |
| | COD_IS | Irrig. schedule method |
| | CDAYI* | Day of irrigation event |
| | CDEPTH* | Irrigation depth |

results (see Section 2.2), is read to build a new database where seasonal values are stored. From these seasonal results, this module provides a statistical description (average, standard deviation and coefficient of variation) of the temporal and spatial variability of the main variables (such as yield, biomass or water productivity), calculating seasonal averages, temporal variability, etc. All the databases generated by this module are stored in dBase files and are ready for their visualization in a GIS platform.

### 2.4.2. Visualization module

This module facilitates the spatial visualization and interpretation of AquaCrop results. The graphical base of the module of visualization is a field map (Shape file), which is an external input of this module (Fig. 3). This graphical information is linked to a database in where all the information associated to each field is stored following the format required by the GIS software (dBase file).

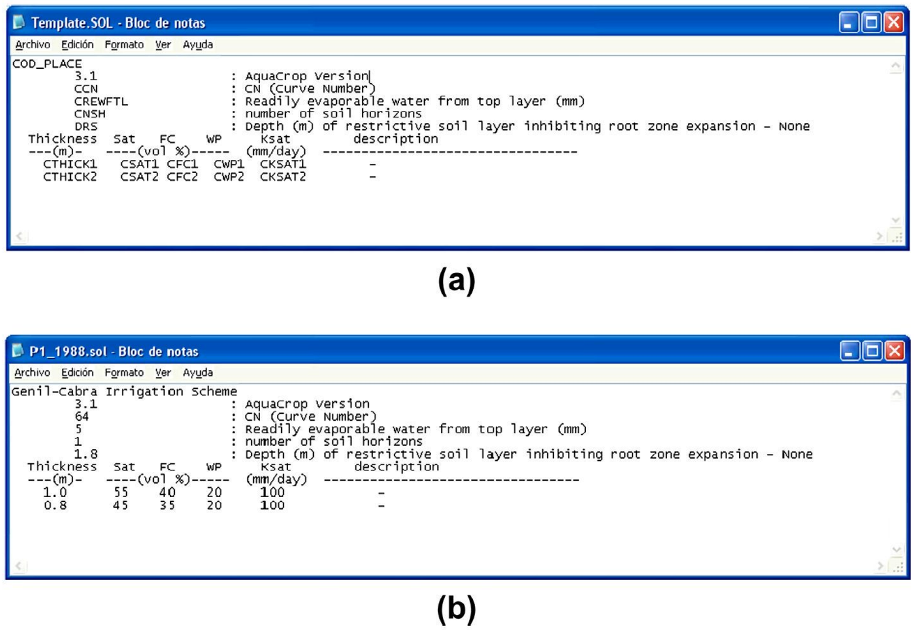
AquaGIS generates new databases (called visualization databases, VD, Fig. 3) with all the results obtained in the Execution module. AquaGIS generates these visualization databases according to the user preferences, and store them as dBase files. The link between the visualization database and the GIS is made by replacing the original dBase file associated to the field map with a new one, the visualization database (VD). To carry out this replacement, VD includes a row with the code/name of each field mapped, identical to another one included in the original dBase file associated to the field map, this now being the link between the map and the VD. In addition VD also includes additional rows for storing the desired parameters to be mapped by the user (e.g., yield, water productivity, etc.). The conventional tools that all GIS have were incorporated here, including the zoom and pan tools. In addition, a seek function has been included to find fields with specific information within the results generated by AquaCrop. Also, a tool has been included for obtaining information of a selected field by the user.

For mapping visualization two additional tools have been included in this module. The first one allows any input or result to be displayed on a map, shown with ramped colors that facilitate the spatial visualization. The second tool is an innovative application that allows visualizing multiple maps which describe the temporal evolution of the results provided by AquaCrop. This visualization tool is made by alternatively mapping daily/weekly/monthly VD sequentially at regular intervals using the GIS. Thus, for example it would be possible to map in a GIS the temporal evolution of biomass for the whole area and throughout the season.

MapObjects software was used for the visualization module although the generated maps may be visualized using any other GIS software because the results are stored in Shape and dBase files. Analogous to AquaData, AquaGIS may be used in conjunction with any crop simulation model where the output files are stored as text files and there is a plug-in version of the model.

## 2.5. Update procedure for AquaData and AquaGIS

FAO frequently updates AquaCrop software to add new calibrated crops or processes, and to improve certain features of the model. The last version was launched on mid 2012 and



Template.SOL - Bloc de notas

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```
COD_PLACE
        3.1                 : AquaCrop Version
        CCN                 : CN (Curve Number)
        CREWFTL             : Readily evaporable water from top layer (mm)
        CNSH                : number of soil horizons
        DRS                 : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       description
  ---(m)-   ----(vol %)-----  (mm/day)  ---------------------------------
    CTHICK1   CSAT1 CFC1  CWP1  CKSAT1         -
    CTHICK2   CSAT2 CFC2  CWP2  CKSAT2         -
```

(a)

P1_1988.sol - Bloc de notas

Archivo Edición Formato Ver Ayuda

```
Genil-Cabra Irrigation Scheme
        3.1                 : AquaCrop Version
        64                  : CN (Curve Number)
        5                   : Readily evaporable water from top layer (mm)
        1                   : number of soil horizons
        1.8                 : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       description
  ---(m)-   ----(vol %)-----  (mm/day)  ---------------------------------
    1.0       55    40    20     100           -
    0.8       45    35    20     100           -
```

(b)

**Fig. 2.** (a) The soil template of AquaData and (b) the soil file (.SOL) for AquaCrop generated by AquaData (in this case for field P1_1988).

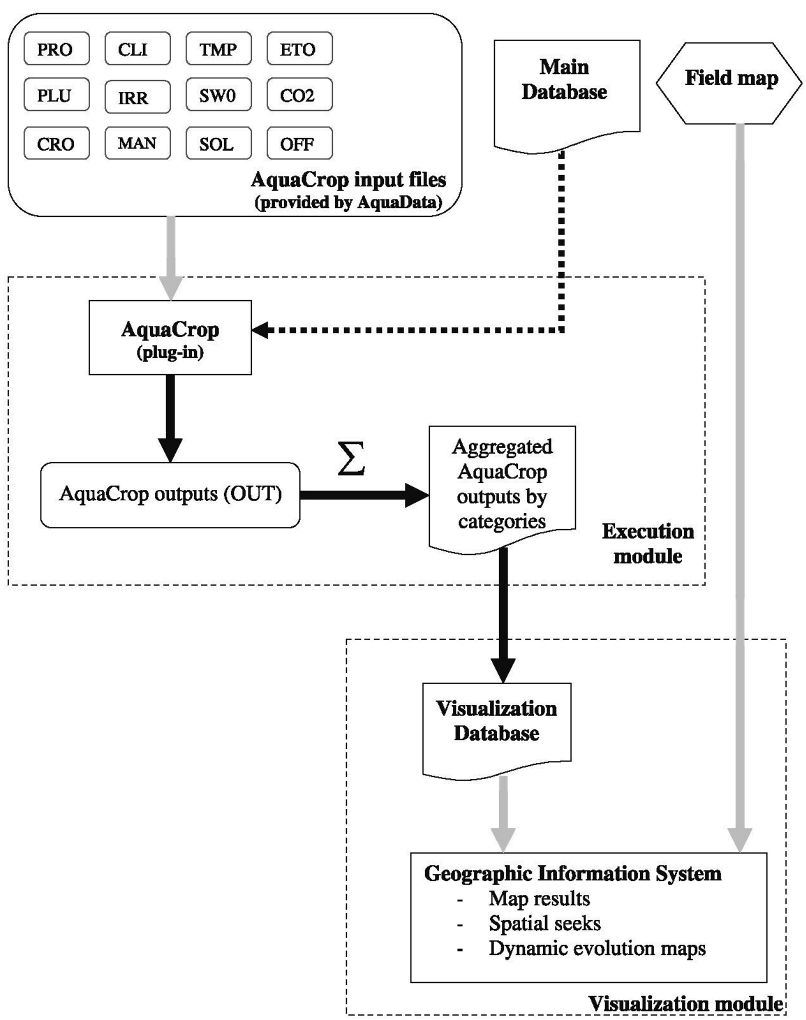


**Fig. 3.** Diagram of AquaGIS, including the execution and visualization modules. Operation is guided by the main database and visualization is based on a map of the fields.

**Table 4**
Simulated climate for control runs (CU, period 1961–1990) and future (A2, period 2070–2099) scenarios for 5 specific locations and four climate models: PROMES (PR), REMO (RE), HadRM3H (HA) and RACMO (RA).

| M | Location | Cordoba | | Sevilla | | Jerez | | Antequera | | Trigueros | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coordinates | 341642 | 4192085 | 238115 | 4156016 | 767119 | 4059604 | 361379 | 4102383 | 692989 | 4139456 |
| | Run | CU | A2 | CU | A2 | CU | A2 | CU | A2 | CU | A2 |
| PR | Rainfall (mm) | 315.6 | 227.6 | 320.2 | 219.5 | 435.9 | 303.7 | 266.6 | 176.7 | 381.8 | 268.0 |
| | CV Rainfall (%) | 0.39 | 0.47 | 0.42 | 0.48 | 0.44 | 0.54 | 0.43 | 0.50 | 0.42 | 0.49 |
| | Tmax (°C) | 23.0 | 28.1 | 23.2 | 28.0 | 22.0 | 26.3 | 21.9 | 26.9 | 22.5 | 27.2 |
| | Tmin (°C) | 14.1 | 18.4 | 14.5 | 18.6 | 14.0 | 17.5 | 12.8 | 17.0 | 14.2 | 18.1 |
| RE | Rainfall (mm) | 411.4 | 262.2 | 368.3 | 230.3 | 542.0 | 344.7 | 356.3 | 230.9 | 425.5 | 301.8 |
| | CV Rainfall (%) | 0.33 | 0.38 | 0.38 | 0.44 | 0.40 | 0.54 | 0.35 | 0.39 | 0.43 | 0.50 |
| | Tmax (°C) | 25.7 | 30.4 | 26.5 | 30.7 | 25.3 | 29.1 | 23.0 | 27.5 | 24.8 | 28.5 |
| | Tmin (°C) | 12.8 | 17.0 | 14.6 | 18.5 | 14.7 | 18.0 | 10.5 | 14.4 | 15.0 | 18.5 |
| HA | Rainfall (mm) | 270.8 | 153.4 | 281.5 | 146.7 | 253.0 | 109.4 | 434.2 | 204.2 | 271.1 | 114.5 |
| | CV Rainfall (%) | 0.34 | 0.42 | 0.36 | 0.43 | 0.34 | 0.38 | 0.34 | 0.48 | 0.37 | 0.40 |
| | Tmax (°C) | 25.8 | 30.6 | 25.6 | 30.2 | 24.8 | 28.8 | 23.3 | 28.3 | 24.9 | 29.3 |
| | Tmin (°C) | 11.6 | 15.8 | 12.6 | 16.3 | 12.3 | 16.0 | 10.4 | 14.3 | 12.2 | 16.1 |
| RA | Rainfall (mm) | 288.7 | 200.6 | 349.5 | 227.7 | 381.0 | 250.6 | 377.4 | 243.2 | 292.6 | 201.2 |
| | CV Rainfall (%) | 0.37 | 0.43 | 0.40 | 0.47 | 0.38 | 0.54 | 0.33 | 0.44 | 0.41 | 0.49 |
| | Tmax (°C) | 21.5 | 26.9 | 22.5 | 27.7 | 22.6 | 27.2 | 21.8 | 27.4 | 22.8 | 27.3 |
| | Tmin (°C) | 9.4 | 13.9 | 10.7 | 15.0 | 13.0 | 16.8 | 10.3 | 14.8 | 12.9 | 16.8 |
| Avg | Rainfall (mm) | 321.6 | 210.9 | 329.9 | 206.1 | 402.9 | 252.1 | 358.6 | 213.7 | 342.8 | 221.4 |
| | CV Rainfall (%) | 0.36 | 0.43 | 0.39 | 0.46 | 0.39 | 0.50 | 0.36 | 0.45 | 0.41 | 0.47 |
| | Tmax (°C) | 24.0 | 29.0 | 24.4 | 29.2 | 23.7 | 27.8 | 22.5 | 27.5 | 23.7 | 28.0 |
| | Tmin (°C) | 12.0 | 16.3 | 13.1 | 17.1 | 13.5 | 17.1 | 11.0 | 15.1 | 13.6 | 17.4 |

incorporated processes such as capillary rise from groundwater table (Raes et al., 2012). Obviously, AquaData and AquaGIS will have to be updated to the new AquaCrop versions. Due to the simplicity of both utilities, the update procedure only requires identifying the changes in the input/output format files and the generation of those new input files which are included in the new AquaCrop version. Specifically, the update procedure from version 3.1+ to the new 4.0 version consists in the inclusion of two new parameters for capillary rise characterization in the soil files (.SOL), the inclusion of the salinity (ECe) of each soil layer in the SW0 files and the inclusion of a new input file (.GWT) where groundwater table depth and salinity are included. All these changes would only require changes in the templates files with the inclusion of the additional parameters and the generation of a new template for the file .GWT, following the procedure described in Section 2.3.3.

Current AquaGIS version is completely functional with v. 4.0 AquaCrop. However, minor modifications in AquaGIS could provide the generation of new maps due to the inclusion in the OUT file generated by AquaCrop v.4.0 of outputs related the upward movement of water by capillary rise, salts drained or that move upward and are stored in the soil profile.

Similarly, AquaCrop could provide (currently or in future versions) some functions which are not considered in the current version of AquaData/AquaGIS, for example, generating different irrigation schedules with AquaCrop. The modifications needed in AquaData to generate these schedules would only require changes in the IRR file, modifying the parameter to indicate AquaCrop that the irrigation scheduling must be generated, and including the irrigation scheduling data (timing and the volume of irrigation applied).

### *2.6. Impacts of climate change on wheat yields: regional simulation with AquaCrop*

To illustrate the use of AquaData and AquaGIS, a simulation study of climate change impacts on wheat yields was carried out for a region in Andalusia, Southern Spain. Daily weather data generated by four regional climate models (PRUDENCE project; Christensen et al., 2007) were considered. The models were: PROMES (Castro et al., 1993), REMO (Jacob, 2001), HadRM3H (Jones et al., 1995) and RACMO (Lenderink et al., 2003). These models have been described extensively (Christensen and Christensen, 2007) and their outputs have been used for evaluating impacts of climate change on crop production (Mínguez et al., 2007). These four regional climate models provided 60 years of daily weather data: 30 years for a control period, from 1961 to 1990, and 30 years for a future period spanning from 2070 to 2099, under the IPCC Special Report on Emission Scenarios-A2 scenarios. The domain of the study was covered by 27 cells (each defined as a square polygon with a $0.5° \times 0.5°$ longitude/latitude resolution, of around 2500 $km^2$) of each model, all located within Andalusia. These cells encompass the major wheat growing areas of Andalusia. The climate change effects on wheat yield were assessed using AquaCrop, which incorporates a flexible response of the water productivity parameter to the change in $CO_2$ concentration (Hsiao et al., 2012).

The reference evapotranspiration ($ET_o$) needed to run AquaCrop needs to be calculated with the daily weather data generated by the models. Even though the recommended $ET_o$ equation is the Penman–Monteith formulation (Steduto et al., 2012), as wind speed and humidity have high level of uncertainty under the A2 scenario (Rockel and Woth, 2007), the Hargreaves equation that

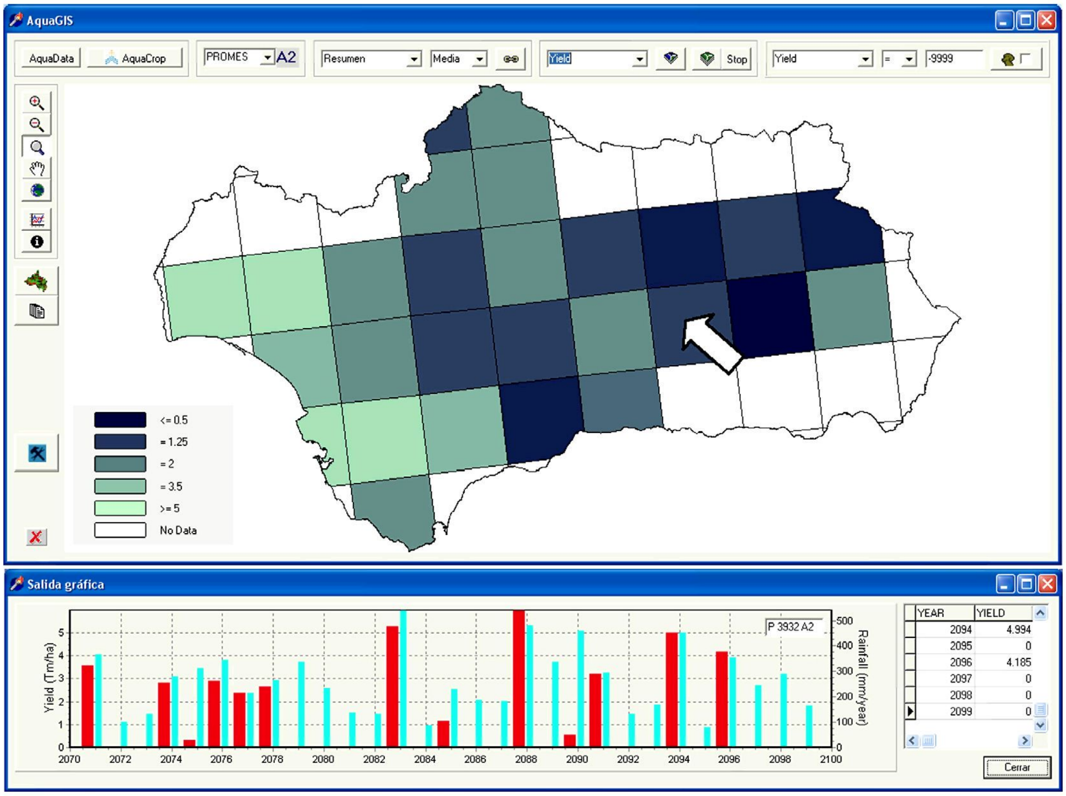


**Fig. 4.** AquaGIS screen showing the average yield in the period 2070–2099 for the PROMES climate model under scenario A2 for Andalusia and the annual yield (in red) and rainfall (in blue) for cell 3932 indicated with a white arrow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

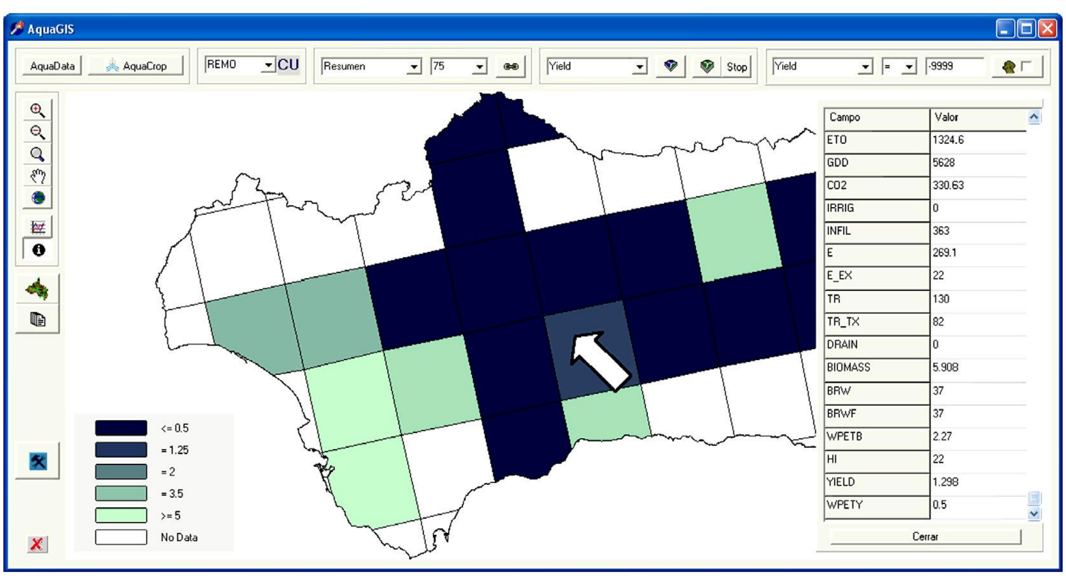


**Fig. 5.** AquaGIS screen showing the seasonal yield values provided by AquaCrop for REMO climate model for 1975. On the right, AquaCrop results for cell 9823 indicated by the arrow.

uses only temperature data was used here for $ET_o$ determination, because it has been shown to provide $ET_o$ values well correlated with those calculated by the Penman–Monteith equation under Southern Spain conditions (Espadafor et al., 2011). Soil input parameters were determined considering averaged soil data from previous studies (COP-CMA, 2006), while cropping practices and crop input parameters, such as sowing date, sowing density or the previous crop (needed for computation of stored soil water at planting) were determined based on general practices of the region. Only rainfed conditions were considered.

The future climate for Southern Spain, simulated with the regional climate models, depicted a general trend of reduced rainfall, increase in inter-annual variability, and increase in maximum and minimum temperatures (Table 4, in agreement with Christensen and Christensen, 2007). Averaging all model results, the reduction in rainfall in the 2070–2099 period was around 37% relative to the

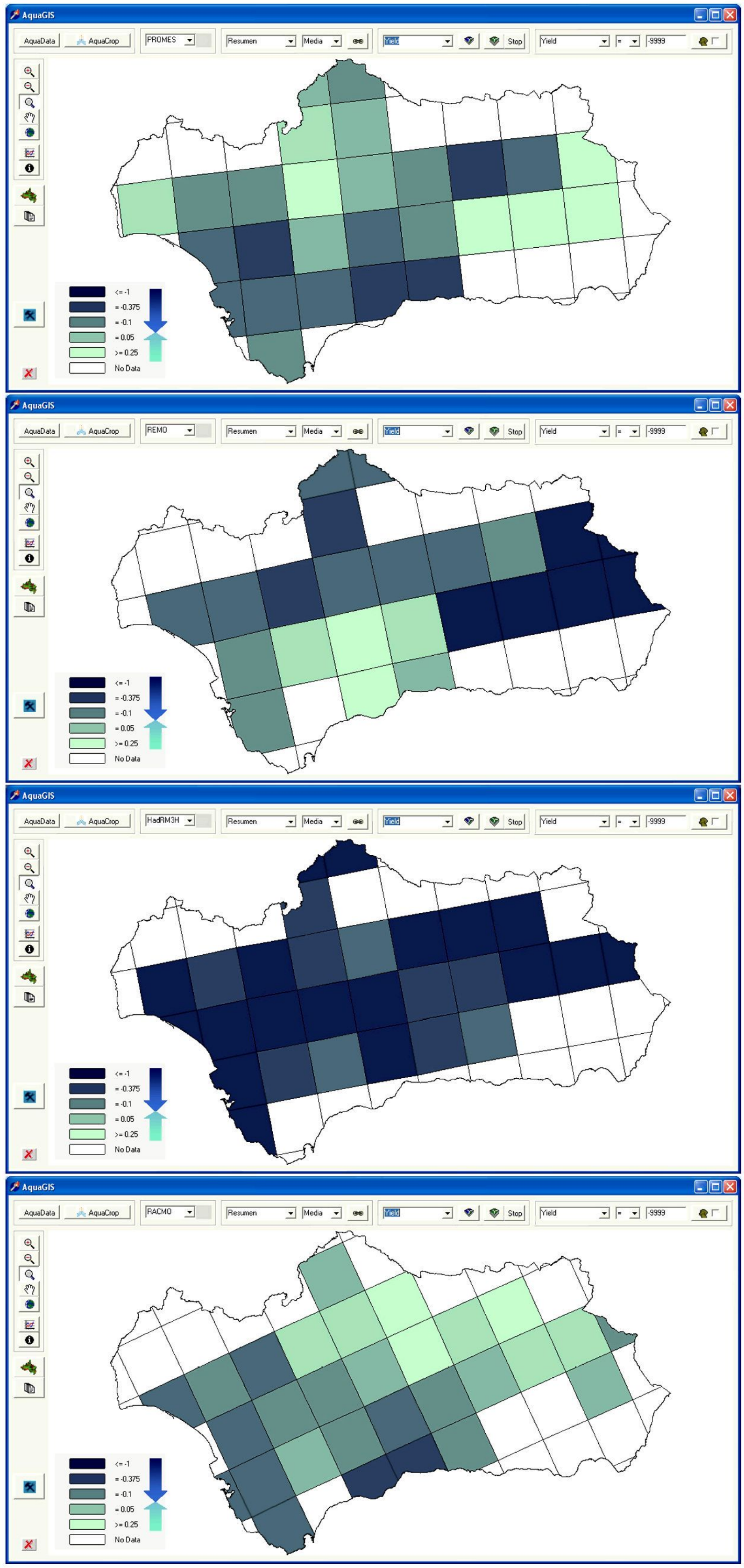


**Fig. 6.** AquaGIS snapshots showing AquaCrop results for PROMES, REMO, HadRM3H and RACMO climate models (respectively from the top to the bottom), mapping the differences in wheat yields (percentages) for current (1961–1990 period) and future climate condition (2070–2099 period). Arrows indicate the trend in the simulated wheat yield with respect to current period.

**Table 5**
Simulated yield, inter-annual yield variability (CV) and water productivity ($WP_{ET}$) using AquaCrop for control runs (CU, period 1961–1990) and future (A2, period 2070–2099) scenarios for five specific locations and four climate models: PROMES (PR), REMO (RE), HadRM3H (HA) and RACMO (RA).

| M | Location | Cordoba | | Sevilla | | Jerez | | Antequera | | Trigueros | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coordinates | 341642 | 4192085 | 238115 | 4156016 | 767119 | 4059604 | 361379 | 4102383 | 692989 | 4139456 |
| | Scenario | CU | A2 | CU | A2 | CU | A2 | CU | A2 | CU | A2 |
| PR | Yield (T $ha^{-1}$) | 2.32 | 2.49 | 2.90 | 2.75 | 4.90 | 4.34 | 1.64 | 1.24 | 4.56 | 4.30 |
| | CV Yield (%) | 1.24 | 1.49 | 1.12 | 1.32 | 0.63 | 1.00 | 1.51 | 2.27 | 0.67 | 0.97 |
| | $WP_{ET}$ (kg $m^{-3}$) | 0.84 | 1.07 | 1.09 | 1.36 | 1.75 | 1.98 | 0.58 | 0.50 | 1.64 | 2.05 |
| RE | Yield (T $ha^{-1}$) | 2.09 | 1.86 | 2.52 | 2.21 | 3.61 | 3.27 | 1.47 | 1.64 | 2.77 | 2.12 |
| | CV Yield (%) | 1.41 | 1.74 | 1.15 | 1.52 | 0.93 | 1.23 | 1.68 | 1.60 | 1.07 | 1.51 |
| | $WP_{ET}$ (kg $m^{-3}$) | 0.62 | 0.69 | 0.92 | 1.05 | 1.28 | 1.40 | 0.43 | 0.63 | 1.04 | 1.05 |
| HA | Yield (T $ha^{-1}$) | 0.66 | 0.53 | 1.45 | 0.54 | 0.88 | 0.09 | 3.09 | 1.20 | 1.63 | 0.03 |
| | CV Yield (%) | 2.42 | 3.09 | 1.57 | 2.97 | 2.19 | 4.25 | 0.94 | 2.00 | 1.48 | 3.85 |
| | $WP_{ET}$ (kg $m^{-3}$) | 0.22 | 0.26 | 0.51 | 0.28 | 0.30 | 0.07 | 0.83 | 0.51 | 0.55 | 0.03 |
| RA | Yield (T $ha^{-1}$) | 1.39 | 1.67 | 3.04 | 2.59 | 3.99 | 3.39 | 3.21 | 2.65 | 3.04 | 2.59 |
| | CV Yield (%) | 1.39 | 1.54 | 0.94 | 1.32 | 0.83 | 1.24 | 0.91 | 1.29 | 0.98 | 1.47 |
| | $WP_{ET}$ (kg $m^{-3}$) | 0.43 | 0.67 | 0.91 | 1.02 | 1.35 | 1.38 | 0.91 | 1.02 | 1.11 | 1.18 |
| Avg | Yield (T $ha^{-1}$) | 1.62 | 1.64 | 2.48 | 2.02 | 3.35 | 2.77 | 2.35 | 1.69 | 3.00 | 2.26 |
| | CV Yield (%) | 1.62 | 1.97 | 1.20 | 1.78 | 1.15 | 1.93 | 1.26 | 1.79 | 1.05 | 1.95 |
| | $WP_{ET}$ (kg $m^{-3}$) | 0.53 | 0.67 | 0.86 | 0.93 | 1.17 | 1.21 | 0.69 | 0.67 | 1.09 | 1.08 |

1961–1990 period, with an increase in inter-annual variability of around 15%. For average maximum and minimum temperatures the increase was 18% and 28% respectively. To simulate the impact of such changes in weather on wheat yields over the chosen region AquaCrop was run 6480 times (60 years × 4 models × 27 cells). We estimated that around 540 h or 68 working days (assuming 5 min per input file set consisting of eight files; Table 1), would be required to prepare the files manually. In addition, we estimated that the processing of output files for analysis and visualization would require a similar amount of time totaling a required time of around 1080 h to carry out the simulations manually.

## 3. Results and discussion

### *3.1. AquaCrop simulation runs assisted by AquaData and AquaGIS*

The model was run using AquaData to generate the input files (around 51,840 files) and AquaGIS to analyze the output 6480 file sets from AquaCrop. The total processing time was less than 1 h. In addition to the time savings, AquaData and AquaGIS provided greater reliability of the results because all input and output files were free of operational errors (for example, climate series must be accurately correlated temporally and spatially), errors which are very common when thousands of files are processed. Finally, AquaGIS provided a GIS tool to access the geographic and alphanumeric information and to visualize the spatial and temporal variations of AquaCrop results (Figs. 4–6).

AquaGIS provides three ways to visualize the results obtained from AquaCrop; as a map, a bar graph, or a table, as desired by the user. In Fig. 4, a snapshot of AquaGIS is shown, which maps the simulated average wheat yield for the period 2070–2099 using the weather output of PROMES. Fig. 4 also shows a bar graph of the annual rainfall for cell 3932 (indicated with an arrow). In Fig. 5, a table of numerical results for cell 9823 (indicated by an arrow) simulated by AquaCrop is shown as a part of the map of wheat yield for the year 1975 with weather data provided by the REMO model.

### *3.2. Spatial analysis of the impact of climate change on wheat yield*

Table 5 and Fig. 6 describe the simulated wheat yield, water productivity ($WP_{ET}$) and its inter-annual variability for different representative locations in Southern Spain under current and future climate scenarios provided by the four regional climate models used in the 6480 simulations carried out by AquaCrop with AquaData and AquaGIS.

The comparison of simulated wheat yield results under current and future climate scenarios, showed significant reduction in wheat yields (around 19.6%) and increases in inter-annual variability (around 43.5%) for the A2 scenarios (Table 5). The variability increase is a common feature in both climate and impact projections and has been reported for crop production in Iberian Peninsula (Ruiz-Ramos and Mínguez, 2010). Also, a slight increase in $WP_{ET}$ (around 4.6%) was detected for the majority of locations and models. Notably, significant differences in yield predictions among models were found (yield reduction varied between 5.3% with the REMO, up to 58.4% with HadRM3H model) and among locations (yield reduction varied between 0.8% in Córdoba, up to 31.4% in Jerez), an indication of the large uncertainties that currently exist in predicting regional yields under future climate (Ruiz-Ramos and Mínguez, 2010).

AquaGIS also provides an option to carry out spatial analysis of the results obtained by AquaCrop. This analysis allowed detecting clear spatial correlations for some models. For RACMO regional climate models a clear positive trend of the impact of climate change on wheat yield in the direction North-East to South-West was found. The cells with greater impact were located in the South and South-West areas of Andalusia (Fig. 6). The results with the PROMES and REMO models had less clear spatial trends, showing the lowest impacts in the Eastern and Southern locations, respectively. The HadRM3H model did not show any spatial trend and the simulations showed a very high impact of climate change in all the analyzed locations. The differences among models were mainly driven by differences in the simulated patterns of rainfall, although differences in temperature and radiation simulations also contributed.

AquaCrop applicability as a decision-support tool for strategic planning may be improved greatly through the use of AquaData and AquaGIS. AquaCrop, linked to these two software tools, can now be efficiently used for the evaluation of management strategies (such as irrigation and sowing date) over a large territory or over the long-term, for scenario analyses such as impact assessment of climate change, and for optimization purposes, where a huge number of input files and simulation runs are required. These applications will facilitate knowledge transfer to technicians and farmers and promote detailed studies using time series at the district, basin, and regional scales.

## 4. Conclusions

The development of AquaData and AquaGIS tools for the automatic running of AquaCrop multiple times improves significantly the applicability of this model to simulate yields for many years and locations, over large areas, or for other applications that require a large number of simulations, providing reliable tools for automated model inputs and outputs management. The two new software tools described here facilitate the AquaCrop simulation runs and the presentation and interpretation of simulation results, allowing spatial visualization and providing a useful spatial tool for further analyses. Although the development of specific computer programs to manage outputs models is not new, this is the first effort that develops such tools for the FAO model AquaCrop (Steduto et al., 2012), including the addition of a GIS tool for spatial analyses.

To illustrate the use of AquaData and AquaGIS and the type of analyses that could be performed, a simple but high-requirement time-consuming study with the traditional application of AquaCrop has been presented. The application of the proposed new software tools saved enormous operating time, ensuring the quality of the results at the same time. The software described here should facilitate significantly the use of AquaCrop at the higher scales and thus the dissemination of simulation results among stakeholders at scales above that of an individual field by combining the use of a friendly environment and the production of thematic maps.

## Note

The AquaData and AquaGIS tools and regular updates will be available to researchers upon request. Please contact the corresponding author.


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